Texas A&M University in the JET Collaboration

Final Report

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Summary

The main focus of the group at Texas A&M has been the development and implementation of a hadronization model suitable to calculate hadronization of jet showers in heavy ion collisions event by event. The JET working group created for this purpose had co-PIs R. J Fries and C. M. Ko, and student K. Han from Texas A&M as constant members and was convened by R. J. Fries. The group successfully developed a hybrid model of parton recombination and remnant string fragmentation including recombination with thermal partons. A code realizing this model was developed and shared with other JET members. In addition, the group at Texas A&M worked on both open and hidden heavy flavor probes. In particular, they developed a description of heavy flavor hadronization based on recombination, and consistent with in-medium scattering rates of heavy quarks, and suggested the D_s meson as a precise probe of the hadronization mechanism. Another noteworthy focus of their work were electromagnetic probes, in particular dileptons and photons from interactions of jets with the medium. In the soft sector the group has made several contributions to modern topics, e.g. the splitting of elliptic flow between isospin partners, and the role of the initial strong gluon fields. One student in the group received his Ph. D. during the funding period and three more are expected to receive their Ph.D.s within the next 6 months.

I. Accomplishments

1) Jet Fragmentation via Shower Parton Recombination (Fries, Ko and collaborator)

We have studied hadron production in jets by applying quark recombination to jet shower partons on an event-by even basis [23]. We augment perturbative vacuum jet showers, for example those obtained from PYTHIA, by additional non-perturbative effects like gluons splitting into quark-antiquark pairs. We then apply an instantaneous recombination model in phase space, using Wigner functions for mesons and baryons, to calculate the recombination probability for pairs or triplets of quarks and antiquarks. The hadron Wigner functions are based on harmonic oscillator potentials, with quarks modeled as Gaussian wave packets which leads to overlap integrals which are positive definite and amenable to Monte Carlo techniques. We throw dice to determine recombined hadrons from those probabilities. Subsequently we connect leftover partons with strings which are treated according to the Lund fragmentation model (as incorporated in PYTHIA). We have computed hadron spectra in e^++e^- collisions at √sNN= 200 GeV. Including contributions from resonance decays, we have found that the resulting longitudinal and transverse (with respect to the jet axis) momentum spectra for pions, kaons, and protons reproduce reasonably those from the string fragmentation as implemented in PYTHIA [35].

2) Jet Fragmentation in the Presence of a Hot Medium

We have extended our jet shower hadronization model to include hadron production from quenched jets in the quark-gluon plasma produced in heavy ion collisions. In this case shower partons have to be propagated to the $T=T_c$ hypersurface. The thermal quark distribution on the critical surface is sampled and recombination probabilities of all possible quark/antiquarks pairs and triplets are considered as long as they contain at least one shower parton. An enhanced production of intermediate-momentum hadrons is obtained as a result of the recombination of shower partons from quenched jets with thermal partons in the quark-gluon plasma [36].

3) Leadership for the JET Working Group on Quark Recombination (Fries, Ko)

A dedicated Quark Recombination (QR) working group, convened by R. J. Fries, has existed since the beginning of the JET collaboration. Its charge was to work out a general formalism for quark recombination of jet showers in vacuum and in a medium, and to implement it in an event-by-event Monte Carlo code. The working group has met regularly online. Over the past year the meetings were usually shared between the QR and the shower Monte Carlo working group. The results discussed in the two previous items are a direct result of this working group. A first version of the Texas A&M hadronization MC code is now implemented by both the Wayne State and the Berkeley/CCNU groups in their shower MC codes.

4) Subthreshold cascade baryon production (Ko and collaborators)

Using a gauged flavor SU(3)-invariant hadronic Lagrangian, we have calculated the cross sections of the strangeness-exchange reactions for the production of doubly strange cascade baryon from the interaction of singly strange hyperons in the Born approximation [9,20]. Including these cross sections in the relativistic Vlasov-Uehling-Uhlenbeck (RVUU) transport model, we have obtained an order of magnitude enhancement in the yield of cascade baryon than the prediction from the statistical model for heavy ion collisions at subthreshold energies, consistent with the experimental observation by the HADES Collaboration at GSI.

5) Mean-field effects in baryon-rich matter (Ko and collaborators)

Within the framework of a multiphase transport (AMPT) model that includes both initial partonic and final hadronic interactions [12], we have shown that including mean-field potentials in the baryon-rich hadronic matter leads to a splitting of the elliptic flows of particles and their antiparticles, thus providing a partial explanation for the larger p than pbar, K+ than K-, and π- than π+ elliptic flows observed in the beam energy scan (BES) program at the Relativistic Heavy-Ion Collider (RHIC) [7,14]. Using a partonic transport model based on the Nambu-Jona-Lasinio (NJL) model, we have further found a similar effect on the quark and antiquark elliptic flows from the vector mean field in the baryon-rich quark matter [26]. Results from including both the partonic and the hadronic mean-field potentials in the AMPT model further indicate that an appreciable vector mean field in the partonic matter is needed to describe the observed elliptic flow differences between particles and their antiparticles [28]. To further understand the properties of baryon-rich quark-gluon plasma, we have used both the quantum linear response theory and the semi-classical Vlasov equation to study the growth rate of its unstable modes due to the spinodal instability [34].

6) Anisotropic flows and dihadron correlations (Ko and collaborators)

Using the AMPT model, we have continued to study heavy ion collisions at the Large Hadron Collider (LHC) and obtained a reasonable description of the ALICE experimental data on the higher-order anisotropic flows and the two dimensional dihadron pseudorapidity and azimuthal angular correlations as well as the experimental results from the CMS Collaborations on the short- and long-range rapidity difference dihadron azimuthal correlations [2,11].

7) Quarkonia production (Ko and collaborators)

With the in-medium properties of quarkonia calculated from the screened Cornell potential and the perturbative Quantum Chromodynamics (QCD), we have studied quarkonia production in relativistic heavy-ion collisions by including both the initial dissociation and the subsequent thermal decay as well as the regeneration of quarkonia in the produced quark-gluon plasma (QGP) [19,24]. A good description has been obtained for the nuclear modification factors of charmonia measured in heavy ion collisions at SPS, RHIC and LHC [1] and of bottomonia measured at RHIC and LHC [5]. Also, an application of our model to charmonium production in p+Pb collisions at the LHC shows that the hot medium effects are also present [29,30]. We have further investigated the heavy quark non-equilibrium effect [8] and the effect of initial-state fluctuations on quarkonia production [10,21], the formation time of quarkonia [17,31] and the heavy quark potential [27] in the quark-gluon plasma, the validity of the dipole approximation used in calculating the chamronium dissociation cross section [25], and the spin asymmetry of J/ψ in peripheral heavy ion collisions at LHC [32], and the effect of heavy quark correlations on quarkonia regeneration from the QGP [33].

8) Dilepton production (Ko and collaborators)

In collaboration with Elena Bratkovskaya of University of Frankfurt and Frankfurt Institute for Advance Studies, and Olena Linnyk and Wolfgang Cassing of Giessen University, we have studied dilepton production in heavy ion collisions within the microscopic parton-hadron-string dynamics (PHSD) transport approach that incorporates explicit partonic degrees of freedom and dynamical hadronization as well as the more familiar hadronic dynamics in the final reaction stage [13]. A comparison to the data of the NA60 Collaboration shows that the measured dilepton yield is well described by including the collisional broadening of vector mesons, and the spectra in the intermediate mass region (1 GeV $< M <$ 2.5 GeV) are dominated by quark-antiquark annihilation in the nonperturbative QGP [3]. For heavy ion collisions at RHIC, we have compared our results to the data from the PHENIX Collaboration to study the relative importance of different dilepton production mechanisms and pointed out the regions in phase space where partonic channels are dominant [6]. We have further made explicit predictions for dileptons within the acceptance of the STAR detector system and compared with the preliminary data. For central Pb+Pb collisions at LHC, we have found a moderate increase of the low mass dilepton yield essentially due to the in-medium modification of the rho-meson, pronounced traces of the partonic degrees of freedom in the intermediate mass regime, and a larger dilepton yield from the strongly interacting QGP than that from the semi-leptonic decays of open charm and bottom mesons [15].

9) Event-by-event jet quenching (Ko and collaborators)

In collaboration with Hanzhong Zhang of China Central Normal University, we have studied the effect of initial state fluctuations on jet energy loss in relativistic heavy-ion collisions in a 2+1 dimension ideal hydrodynamic model [18,22]. Within the next-to-leading order perturbative QCD description of hard scatterings, we have found that a jet loses slightly more energy in an expanding quark-gluon plasma that is described by the hydrodynamic evolution with fluctuating initial conditions compared to the case with smooth initial conditions, with the effect larger in non-central than in central relativistic heavy ion collisions and also for jet energy loss that has a linear than a quadratic dependence on its path length in the medium.

10) Exotic hadrons production (Ko and collaborators)

In collaboration with Su Hong Lee of Yonsei University, Akira Ohnishi of Yukawa Institute for Theoretical Physics and a number of other hadron physicists in Japan, we have studied multi-quark hadron production from relativistic heavy ion collisions using the quark coalescence model [4,16]. We have found that compared to hadrons of normal quark numbers, the yield of an exotic hadron is typically an order of magnitude smaller when it is a compact multiquark state and a factor of two or more larger when it is a loosely bound hadronic molecule, thus providing the possibility of resolving their structures, which is a longstanding problem in hadronic physics, from their yields in relativistic heavy ion collisions.

11) Initial Classical Gluon Fields (Fries and collaborators)

Together with J. Kapusta and Y. Li we have developed a framework to solve the classical Yang-Mills equations for colliding nuclei analytically for small times. Subsequently, with G. Chen we have used this approach to calculate the event-averaged energy momentum tensor $T^{\mu\nu}$ of the initial gluon field in nuclear collisions. The two most interesting results of this study are (a) analytic expressions for the time evolution of transverse and longitudinal pressure; (b) analytic expressions for the space-time structure of the transverse flow field. It turns out that Gauss' Law mandates the existence of a rapidity-odd flow field that can lead to directed flow in finite impact parameter collisions and to interesting asymmetries in asymmetric collisions systems like Cu+Au and p+Pb. Our results are valid only at the earliest times, up to $\tau \sim 1/Q_s$. However they could be useful, either directly as initial conditions for hydrodynamics with large dissipative stress, or as input for simulations of thermalizing color fields. While the current analytic results are event-averaged, it is straight forward to construct an event-generator based on this method. This work has been published in [37, 38].

12) Rapidity Structure of Colliding Sheets of Color Glass (Fries and collaborators)

One shortcoming of the classical McLerran-Venugopalan (MV) implementation of color glass condensate is its boost-invariance, owing to the assumption that the colliding nuclei move on the light cone. Together with S. Ozonder we have used a generalization of the

MV model by Lam and Mahlon which calculates corrections for the realistic case of nuclei close to, but off the light cone. This incomplete (finite) Lorentz boost of the nuclei gives them a finite longitudinal thickness. In turn this makes the space-time structure of the collision much more complicated. We have calculated the rapidity distribution $d\varepsilon/d\eta$ of the energy density immediately after the collision, using a set of assumptions that should hold as long as the passing time of the nuclei $\sim R/\gamma$ is much smaller than the inverse saturation scale $1/Q_s$. We find flat distributions (for symmetric systems like Pb+Pb) around midrapidity which fall off towards the beam rapidities. Our main result is a prediction of the rapidity shape and in particular the width of the central plateau. This work has been published in [39].

13) Improved Ideal Hydrodynamics (Fries and collaborators)

Together with R. Rapp and M. He we have suggested that a radical retuning of ideal hydrodynamics (here using AZHYDRO) can lead to improved fits of experimental data from RHIC and LHC. This does not address the limitations of ideal hydrodynamics due to missing viscosities. However, our AZHYDRO tune has proven to be a very versatile tool that has been used for several studies (AZHYDRO is freely available and user-friendly). Our changes involve (i) an equation of state consistent with the latest lattice QCD calculations and with partial chemical equilibrium in the hadronic phase, (ii) an initial flow field which is qualitatively expected on physical grounds, and (iii) an initial profile that is steeper than the usual participant density-based profiles. We constrain the initial state parameters by fitting the total multiplicities of bulk pions, kaons and protons, as well as their spectra and elliptic flow at freeze-out. The crucial improvement is that we can also fit the spectra and elliptic flow of multi-strange hadrons (Omega, Xi, phi) assuming they freeze-out kinetically at the chemical freeze-out temperature of 160 MeV. It has long been suspected that early freeze-out of multi-strange hadrons happens at RHIC and we show that this can be described within the framework of ideal hydrodynamics. Our new tune has a significantly enlarged radial flow around T_c, a feature that is also suggested by our heavy quark diffusion studies. The results of this project have been published in [40].

14) **Relativistic Langevin Formalism (Fries with collaborators)**

With M. He, H. van Hees, P. Gossiaux and R. Rapp we have clarified the relation between the different schemes (pre-point, post-point, etc.) that can be used to implement the Langevin equation in the relativistic regime. The fact that different schemes naively lead to different results is known as the Ito-Stratonovich dilemma. We have pointed out that starting from a microscopic description of a system in terms of a Boltzmann or Fokker-Planck equation one is led to different transport coefficients (drag and diffusion) for each Langevin implementation. Using the correct set of coefficients for each scheme renders all schemes equivalent, while using inappropriate drag and diffusion coefficients will lead to the wrong equilibrium distributions. This work has been published in Phys. Rev. E [41].

15) **Charm Diffusion in the Hadronic Phase (Fries and collaborators)**

We have conducted the first systematic study of the relaxation rates of open charm (D) mesons in hot hadronic matter. We studied interactions with π, K, η, ρ, ω and K* mesons and N and Δ baryons using empirical scattering amplitudes. The study of D mesons in hot hadronic matter is a key ingredient to improve existing approaches to heavy flavors as probes for the quark gluon plasma. We find surprisingly small relaxation times, around 10 fm/c below T_c, consistent with non-perturbative estimates of charm quark relaxation times in QGP just above T_c. The results have been published in [42].

16) **A Comprehensive Framework For Heavy Quark Diffusion and Hadronization (Fries and collaborators)**

We have developed a comprehensive framework for open heavy flavor dynamics in heavy ion collisions using many new and improved tools developed by us. This framework, consisting of Langevin dynamics [41] for heavy quarks and (for the first time) for heavy mesons [42] in a hydrodynamic background [40]. Hadronization is modeled by a hybrid model of resonance recombination and fragmentation. This hadronization model is a crucial step forward and finally achieves consistency through the fact that in-medium heavy quark-light quark scattering rates smoothly go into heavy quark-light quark hadronization rates around T_c. The framework has originally been applied to open heavy flavor observables at full RHIC energies and has been published in [43]. We found an appreciable effect of hadronic diffusion on the elliptic flow of open charm. Subsequently we have also applied our formalism to LHC energies [44] and to the 62 GeV energy run at RHIC [45]. While the description of open heavy flavor observables is generally good we find some tension between R_{AA} and elliptic flow as in many other approaches.

17) The D_s Meson as a Probe of Heavy Quark Hadronization (Fries and collaborators)

We have discovered that the D_s meson can be used as a rather sensitive probe for the charm hadronization mechanism in heavy ion collisions. Coalescence with strange quarks picks up the enhanced strangeness in heavy ion collisions while fragmentation into D_s mesons would not do that. Thus the nuclear modification factor R_{AA} is enhanced in the former scenario compared to the latter. In practice one can compare the D_s and D meson R_{AA}'s. Since charm diffusion up to the critical temperature is the same for both systems any difference has to come from hadronization. Our framework in which recombination rates are fixed almost parameter free predicts that strangeness enhancement leads to a significant enhancement of D_s over D meson R_{AA}. In turn an exact measurement could map out the recombination rate rather accurately. This result has been published as a Physical Review Letter [46]. The ALICE collaboration has since presented a preliminary measurement of the D_s meson R_{AA} which exhibits an enhancement roughly commensurate with our prediction. As a second benefit, the D_s meson v_2 compared to the D meson v_2 can give valuable constraints on the charm diffusion in the hadronic phase since the D_s, similar to the multi-strange hadrons, doesn't easily form resonances in the hadronic phase and should thus freeze-out very early.

18) Jet-Triggered Photons (Fries and Collaborators)

We have studied ways to identify photons from interactions of jets with quark gluon plasma. Those photons are an important but elusive probe of jet-medium interactions. It is difficult to extract them from either the single inclusive direct photon spectrum or the elliptic photon flow. We have suggested to use jets as triggers and to look for photons emitted from Compton back scattering of the away-side jet off QGP. We have worked out corrections to this process due to energy loss of the trigger jets. With the currently available data the residual signal from Compton back-scattering is small, but improvements in jet reconstruction techniques in heavy ion collisions could increase the signal to background ration in the future. This work has been published in [47].

II. Publications Related to the JET Collaboration

[1] T. Song, K. Han, and C. M. Ko, ``Charmonium Production in Relativistic Heavy-Ion Collisions", Phys. Rev. C 84, 034907: 1-11 (2011).

[2] J. Xu and C. M. Ko, ``Higher-Order Anisotropic Flows and Dihadron Correlations in Pb-Pb collisions at √sNN = 2.76 TeV in a Multiphase Transport Model", Phys. Rev. C 84, 044907: 1-6 (2011).

[3] O. Linnyk, E. L. Bratkovskaya, V. Ozvenchuk, W. Cassing, and C. M. Ko, ``Dilepton Production in Nucleus-Nucleus Collisions at Top CERN Super Proton Synchrotron Energy within the Parton-Hadron-String-Dynamics Transport Model", Phys. Rev. C 84, 054917: 1-16 (2011).

[4] S. Cho, T. Furumoto, T. Hyodo, D. Jido, C. M. Ko, S. H Lee, M. Nielsen, A. Ohnishi, T. Sekihara, S. Yasui, and K. Yazaki, ``Exotic Hadrons in Heavy Ion Collisions", Phys. Rev. C 84, 064910: 1-17 (2011).

[5] T. Song, K. C. Han, and C. M. Ko, ``Bottomonia Suppression in Relativistic Heavy-Ion Collisions", Phys. Rev. C 85, 014902: 1-5 (2012).

[6] O. Linnyk, W. Cassing, J. Manninen, E. L. Bratkovskaya, and C. M. Ko, ``Analysis of Dilepton Production in Au+Au Collisions at √sNN = 200 GeV within the Parton-Hadron-String-Dynamics Transport Approach", Phys. Rev. C 85, 024910: 1-10 (2012).

[7] J. Xu, L. W. Chen, C. M. Ko, and Z. W. Lin, ``Effects of Hadronic Potentials on Elliptic Flows in Relativistic Heavy Ion Collisions", Phys. Rev. C 85, 041901(R): 1-4 (2012).

[8] T. Song, K. C. Han, and C. M. Ko, ``Charmonium Production from Nonequilibrium Charm and Anticharm Quarks in Quark-Gluon Plasma", Phys. Rev. C, 85, 054905: 1-8 (2012).

[9] F. Li, L. W. Chen, C. M. Ko, and S. H. Lee, ``Contributions of Hyperon-Hyperon Scattering to Subthreshold Cascade Production in Heavy Ion Collisions", Phys. Rev. C 85, 064902 (2012).

[10] T. Song, K. C. Han, and C. M. Ko, ``Effects of Initial Fluctuations on Bottomonia Suppression in Relativistic Heavy-Ion Collisions", Nucl. Phys. A 897, 141-150 (2012).

[11] C. M. Ko and J. Xu, ``Anisotropic Flow and Dihadron Correlations in Heavy Ion Collisions", Proceedings of Sciences, 057: 1-6 (2012).

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[14] C. M. Ko, L. W. Chen, V. Greco, F. Li, Z. W. Lin, S. Plumari, and T. Song, "Mean-Field Effects on Matter and Antimatter Elliptic Flow", Nucl. Sci. Tech. 24, 050525: 1-7 (2013).

[15] O. Linnyk, W. Cassing, J. Manninen, E. L. Bratkovskaya, P. B. Gossiaux, J. Aichelin, T. Song, and C. M. Ko, ``Dilepton Production In Proton-Proton and Pb+Pb Collisions at √sNN = 2.76 TeV", Phys. Rev. C 87, 014905: 1-16 (2013).

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[17] T. Song, C. M. Ko, and S. H. Lee, ``Quarkonia Formation Time in Quark-Gluon Plasma", Phys. Rev. C 87, 034910: 1-5 (2013).

[18] H. Z. Zhang, T. Song, and C. M. Ko, ``Effects of Initial State Fluctuations on Jet Quenching", Phys. Rev. C 87, 054902: 1-6 (2013).

[19] C. M. Ko, K. C. Han, and T. Song, ``Quarkonia Production in Heavy ion Collisions", Nucl. Phys. A 910-911, 474-477 (2013).

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[30] Y. P. Liu, C. M. Ko, and T. Song, ``Double Ratio of Charmonia in p+Pb Collisions at √sNN = 5.02$TeV", J. Phys.: Conf. Ser. 535, 012011: 1 - 5 (2014).

[31] T. Song, C. M. Ko, and S. H. Lee, ``Quarkonium Formation Time in Relativistic Heavy-Ion Collisions", Phys. Rev. C 91, 044909: 1-5 (2015).

[32] Y. P. Liu, C. M. Ko, and C. Greiner, ``Spin Asymmetry of J/ψ in Peripheral Pb+Pb Collisions at LHC", Phys. Rev. C, submitted.

[33] Y. P. Liu, C. M. Ko, and F. Li, ``Heavy Quark Correlations and the Effective Volume for Quarkonia Production", Phys. Rev. C, submitted.

[34] F. Li and C. M. Ko, ``Spinodal Instability in Baryon-Rich Quark-Gluon Plasma", to be published.

[35] K. C. Han, R. Fries, and C. M. Ko, ``Jet Fragmentation via Recombination of Parton Showers in Vacuum", to be published.

[36] K. C. Han, R. Fries, and C. M. Ko, ``Medium Modifications of Jet Fragmentation", to be published.

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[56] Min He, Rainer J. Fries, and Ralf Rapp, “Scaling of Elliptic Flow, Recombination and Sequential Freeze-Out of Hadrons in Heavy-Ion Collisions”, Phys. Rev. C82, 034907 (2010).

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III. Invited talks related to the JET Collaboration

* indicates talks by students or postdocs

[1] C. M. Ko, ``Strings, Jets and Quark Coalescence in Transport Models", International Workshop on Critical Examination of RHIC Paradigms, Austin, Texas, April 14-17, 2010.

[2] C. M. Ko, ``Overview of Relativistic Heavy Ion Collisions", International Workshop on Exotics in Heavy Ion Collisions, Kyoto, Japan, May 17-29, 2010.

[3] C. M. Ko, ``Exotic Hadrons from Heavy Ion Collisions", International Mini-Symposium on Exotics in Heavy Ion Collisions, Kyoto, Japan, May 19, 2010.

[4] C. M. Ko, “Charmonium Production and Elliptic Flow in Relativistic Heavy Ion Collisions", International Workshop on Hot and Cold Baryonic Matter, Budapest, Hungary, August 15-20, 2010.

[5] C. M. Ko, “Identified Hadrons of Intermediate and High Transverse Momenta in Relativistic Heavy Ion Collisions", International Workshop on Interplay between Soft and Hard Interaction in Particle Production at Ultra-Relativistic Energies, Catania, Italy, September 8-10, 2010.

[6] C. M. Ko, "Particle Production in Heavy Ion Collisions", Colloquium, Institute for Theoretical Physics, University of Frankfurt, Frankfurt, Germany, October 21, 2010.

[7] T. Song, "J/ψ Production and Elliptic Flow in Relativistic Heavy-Ion Collisions", Seminar, McGill University, Montreal, Quebec, Canada, November 25, 2011.

[8] T. Song, "J/ψ Production and Elliptic Flow in Relativistic Heavy-Ion Collisions", International Workshop on Heavy Quark Production in Heavy-Ion Collisions, West Lafayette, Indiana, January 4-7, 2011.

[9] J. Xu, "The Effect of Triangular Flow on Di-hadron Azimuthal Correlations", RIKEN BNL Workshop on Initial State Fluctuations and Final-State Particle Correlations, Upton, New York, February 2-4, 2011.

[10] C. M. Ko, "Triangular Flow in Relativistic Heavy Ion Collisions", International Workshop on In-Medium Effects in Hadronic and Partonic Systems, Obergurgl, Austria, February 21-25, 2011.

[11] C. M. Ko, "Hadronziation by Quark Coalescence", Jet and Electromagnetic Tomography Summer School, Duke University, Durham, North Carolina, June 15-17, 2011.

[12] C. M. Ko, "Triangular flow in Relativistic Heavy Ion Collisions", Workshop on QCD Phase Transitions and Relativistic Heavy Ion Collisions, Hangzhou, China, July 18-20, 2011.

[13] C. M. Ko, "Quarkonia Production in HIC", International Symposium on Non-equilibrium Dynamics, Heraklion, Crete, Greece, August 31 - September 3, 2011.

[14] C. M. Ko, "Anisotropic Flows and Dihadron Correlations in Heavy Ion Collisions", International Workshop on Particle Correlations and Femtoscopy, Tokyo, Japan, September 20-24, 2011.

[15] C. M. Ko, "Quarkonia Production in Heavy Ion Collisions", International Conference on Primordial QCD Matter in LHC Era, Cairo, Egypt, December 4-8, 2011.

[16] C. M. Ko, ``Exotic Hadrons Production in HIC", Workshop on Hyperon-Hyperon Interactions and Searches for Exotic Di-Hyperons in Nuclear Collisions, Brookhaven National Laboratory, Upton, New York, February 29 -March 2, 2012.

[17] C. M. Ko, ``Resonances In AMPT", Workshop on Hadronic Resonance Production in Heavy Ion and Elementary Collisions, Austin, Texas, March 5-7, 2012.

[18] C. M. Ko, ``Anisotropic Flows in HIC", Symposium on Cosmo, Cancer, Criticality and Chromoplasmology, Seattle, Washington, May 6, 2012.

[19] C. M. Ko, ``Dihadron Correlations in AMPT", Workshop on the Ridge Correlation in High-Energy Collisions at RHIC and LHC, Seattle, Washington, May 7-11, 2012.

[20] C. M. Ko, ``Why Particles and Antiparticles Flow Differently?", Symposium on Contemporary Subatomic Physics, Montreal, Canada, June 12-14, 2012.

[21] C. M. Ko, ``Effects of Hadronic Mean-Field Potentials on Elliptic Flows in HIC", Second International Symposium on Non-Equilibrium Dynamics, Heraklion, Greece, June 25-30, 2012.

[22] C. M. Ko, ``Anisotropic Flows and Dihadron Correlations in AMPT", Workshop on Initial State Fluctuations and Final State Correlations in Heavy-Ion Collisions, Trento, Italy, July 2-6, 2012.

[23] C. M. Ko, ``Quarkonia Production in Relativistic Heavy Ion Collisions", Conference on Heavy Ion Collisions in the LHC Era, Qui Nhon, Vietnam, July 15-21, 2012.

[24] C. M. Ko, ``Mean-Field Effects on Elliptic Flow in Relativistic Heavy Ion Collisions", Bertsch Symposium on Nuclear Physics, Seattle, Washington, September 6-9, 2012.

[25] C. M. Ko, “On Physics and Status of AMPT”, International Workshop on Particle Production in Proton-Proton Interactions and Beyond, Bad Liebenzell, Germany, April 19 - May 3, 2013.

[26] C. M. Ko, “Elliptic Flow Difference between Particles and Antiparticles and The EOS of Baryon-Rich Matter”, XXXI Max Born Symposium and HIC for FAIR Workshop on Critical Behavior in Hot Dense QCD, Wroclawski, Poland, June 14 16, 2013.

[27] C. M. Ko, “Hadronization via Coalescence in the AMPT Approach”, International Workshop on Transport Theory in Heavy Ion Collisions, Frankfurt, Germany, July 15 - 17, 2013.

[28] C. M. Ko, “Elliptic Flow as a Probe of the QCD Phase Diagram at Finite Chemical Potential”, 10th International Workshop on QCD Phase Transition and Relativistic Heavy Ion Physics, Chengdu, Sichuan, China, August 8 - 10, 2013.

[29] C. M. Ko, “Fluctuations and Correlations in AMPT”, 2nd Workshop on Initial Fluctuations and Final Correlations, Chengdu, China, August 11 - 14, 2013.

[30] C. M. Ko, “Elliptic Flow of Baryon-Rich Matter”, The 9th International Workshop on Relativistic Aspects of Nuclear Physics, Rio de Janeiro, Brazil, September 23 - 27, 2013.

[31] C. M. Ko, “Mean-Field Effects in Hot Dense Matter”, Tribute to Gerald E. Brown Conference, Stony Brook, New York, November 24 - 26, 2013.

[32] C. M. Ko, “Elliptic flow as a probe of the properties of baryon-rich QGP”, International Workshop on New Frontiers in QCD, Kyoto, Japan, December 2 - 6, 2013.

[33] C. M. Ko,``Particle Production in Heavy Ion Collisions", International Workshop on Simulations of Low and Intermediate Energy Heavy Ion Collisions, Shanghai, China, January 8-12, 2014.

[34] C. M. Ko, ``Jet Fragmentation via Shower Parton Recombination", Third International Symposium on Non-Equilibrium Dynamics, Hersonissos, Crete, Greece, June 9-14, 2014.

[35] C. M. Ko, ``Baryon-Rich Matter in Heavy-Ion Collisions", Workshop on High Temperature and High Density Nuclear Matter Study, Weihai, Shandong, China, August 19-22, 2014.

[36] C. M. Ko, ``Quarkonium Formation Time in Heavy Ion Collisions", Jet Symposium, Montreal, Canada, June 26-27, 2015.

[37] C. M. Ko, ``(Anti-)nulcei Production and Flow in Ultra-Relativistic Heavy-Ion Collisions", EMMI Workshop on Anti-Matter, Hyper-Matter and Exotic Production at the LHC, CERN, Geneva, Switzerland, July 20-22, 2015.

[38] R. J. Fries, "Quark Recombination in Heavy Ion Collisions", JET Collaboration Meeting, Berkeley CA, June 19, 2010.

[39] R. J. Fries, "Jet Chemistry and Contributions to EM Probes", INT Workshop "Quantifying Properties of Hot QCD Matter", Institute for Nuclear Theory, University of Washington, Seattle WA, July 14, 2010.

[40] R. J. Fries, "Event-by-Event Jet Quenching and Fourier Moments", 4th International Conference on Hard and Electromagnetic Probes of High Energy Nuclear Collisions (Hard Probes 2010), Eilat, Israel, October 14, 2010.

[41] R. J. Fries, "Quark Recombination and Quark Scaling – Still Puzzling?", Workshop "From Strong Fields to Colorful Matter", Asheville NC, October 26, 2010.

[42] R. J. Fries, "Event-by-Event Jet Quenching and Fourier Moments", APS Division of Nuclear Physics Meeting (DNP 2010), Santa Fe NM, October 21, 2010.

[43] R. J. Fries, "Some Challenges and Opportunities for Hard Probes", Seminar, McGill University, Montreal Quebec, Canada, November 30, 2010.

[44] G. Chen*, "Behavior of Early Time Gluon Fields in High Energy Nuclear Collisions", APS Division of Nuclear Physics Meeting (DNP 2010), Santa Fe NM, November 6, 2010.

[45] R. J. Fries, "Quark Recombination and Heavy Quarks", Invited Talk, 6th Workshop on High-P_T Physics at the LHC, Utrecht NL, April 6, 2011

[46] R. J. Fries, "Quark Recombination and Heavy Quarks", Nuclear Physics Seminar, University of Minnesota, Minneapolis MN, April 20, 2011

[47] R. J. Fries, “Quark Recombination and Heavy Quark Diffusion”, Quark Matter 2011, Annecy, France, May 23, 2011

[48] M. He*, “Heavy Quark Diffusion and Hadronization in Dense Matter”, Invited talk, Workshop on Heavy-Quark Production in Heavy-Ion Collisions, Purdue University, West Lafayette IN, January 4-6, 2011.

[49] M. He*, “Heavy Flavor Diffusion and Hadronization in Quark-Gluon Plasma”, Invited talk, RHIC & AGS Annual Users' Meeting 2011, Brookhaven National Laboratory, Upton NY, June 20-24, 2011.

[50] M. He*, “Toward a Complete Description of Heavy Flavor Transport in Medium”, Contributed talk, 7th International Workshop on the Critical Point and Onset of Deconfinement, CCNU, Wuhan (China), November 7-11, 2011.

[51] R. J. Fries, “Jet-Triggers for Photons”, Workshop on Jet Measurements at RHIC, Duke University, Durham NC, March 3, 2012.

[52] R. J. Fries, “Quark Recombination”, Workshop Cosmos, Cancer, Criticality and Chromoplasmology, Seattle WA, May 6, 2012.

[53] R. J. Fries, “Jet-Triggered Back-Scattering Photons for QGP Tomography”, 5th Hard Probes 2012, Cagliari (Italy), May 31, 2012.

[54] R. J. Fries, “Flowing Gluon Fields”, Symposium on Contemporary Subatomic Physics (SCSP 2012), McGill University, Montreal QC, June 13, 2012.

[55] R. J. Fries, “Jet-Triggered Back-Scattering Photons for QGP Tomography”, Quark Matter 2012, Washington DC, August 15, 2012.

[56] R. J. Fries, “Toward a Comprehensive Description of Heavy Flavor Dynamics”, KMI Workshop QGP 2012, Kobayashi-Maskawa Institute, Nagoya (Japan), September 26, 2012.

[57] R. J. Fries, “Open Heavy Flavor Probes in Strongly Interacting Nuclear Matter”, Invited Talk, 8th Workshop on High-PT Physics at LHC, Wuhan (China), October 24, 2012.

[58] R. J. Fries, “Recombination for JET Shower MC: Status and Discussion”, JET NLO and Monte Carlo Meeting, Detroit, August 22-23, 2013.

[59] R. J. Fries, “Uncertainties In Jet Event Generators due to Hadronization Scheme, Other Issues with Energy Loss on E-by-E hydro, and the Extraction of Transport Coefficients, RHIC Strategy Meeting, Detroit MI, August 24-25, 2013.

[60] R. J. Fries, “Flowing Gluon Fields: Collective Phenomena in Classical QCD”, 15th Conference on Elastic and Diffractive Scattering (EDS Blois 2013), Saariselka (Finland), September 9-13, 2013.

[61] R. J. Fries, “High Energy Nuclear Collisions: Hard Probes, Heavy Quarks, Strong Gluon Fields”, Colloquium, TAMU Commerce, Commerce TX, September 19, 2013.

[62] R. J. Fries, Flowing Gluon Fields: Collective Phenomena in Classical QCD, 9th Workshop on High PT @ LHC, Grenoble (France), September 25-28, 2013.

[63] R. J. Fries, “Initial Flow of Gluon Fields in Heavy Ion Collisions”, Hard Probes 2013, Cape Town (South Africa), November 4-8, 2013.

[64] R. J. Fries, “Flow and Energy Momentum Tensor From Classical Gluon Fields”, New Frontiers in QCD (NFQCD 2013), Kyoto (Japan), December 2-6, 2013.

[65] R. J. Fries, “Energy Density, Pressure and Flow At Early Times”, XXX. Winter Workshop on Nuclear Dynamics, Galveston TX, April 6-12 2014.

[66] R. J. Fries, “Hadronization for Jet Shower Monte Carlos”, Workshop on “Jet Modifications in the RHIC and LHC Era”, Wayne State University, Detroit MI, August 18-20 2014.

[67] R. J. Fries, “In Medium Hadronization: Hadrons and Jets”, Workshop on “Jet Modifications in the RHIC and LHC Era”, Wayne State University, Detroit MI, August 18-20 2014.

[68] R. J. Fries, “The (3+1)-D Structure of Nuclear Collisions”, II. International Conference on the Initial Stages in High-Energy Nuclear Collisions (IS 2014), Napa CA, December 3-7 2014.

[69] R. J. Fries, “Quark Recombination”, ICPAQGP 2015, VECC Kolkata, India, February 2, 2015.

[70] R. J. Fries, “Quark Recombination”, Seminar, Rice University, April 22, 2015.

[71] R. J. Fries, “Quark Recombination and Jet Shower Hadronization”, JET Symposium, Montreal QC, Canada, June 26, 2015.

[72] R. J. Fries, “Jet Hadronization in Vacuum and in the Medium”, Hard Probes 2015, Montreal QC, Canada, July 1, 2015.

IV) Graduate Student Table

Student	Date Entered Grad. School	Joined Group	Degree Program	Degree Awarded or Expected	Advisor
Kyongchol Han	Aug. 2009	June 2010	Ph.D.	Dec. 2015	Ko
Feng Li	Aug. 2008	June 2010	Ph.D.	Dec. 2015	Ko
Yifeng Sun	Aug. 2013	June 2014	Ph.D.	Aug. 2017	Ko
Zhidong Yang	Aug. 2012	Jan. 2013	Ph.D.	May 2017	Fries
Steven Rose	Aug. 2011	Sep. 2012	Ph.D.	Dec. 2016	Fries
Sidharth Somanathan	Aug. 2010	June 2011	Ph.D.	May 2016	Fries
Guangyao Chen	Aug. 2008	Jan 2009	Ph.D.	Aug. 2013	Fries